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Texture and grain morphology dependencies of saturation magnetostriction in rolled polycrystalline $Fe_{83}Ga_{17}$

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Textured polycrystalline Fe-Ga alloys exhibit magnetostrictive strains of 100 ppm or greater and may function as a mechanically robust actuator/sensing material. Current efforts seek to combine the 300+ ppm magnetostrictive strain performance of [100] oriented single crystals with the mechanical properties of polycrystalline forms. One approach to combining these properties is to control the crystallographic texture through deformation processing such as rolling. To determine the relationship between saturation magnetostriction, degree of texturing, and grain morphology we compare the results of three-dimensional finite element simulations with the analytical solution for a random polycrystal and the experimental responses of rolled polycrystalline $Fe_{83}Ga_{17.}$ Textured specimens were produced through rolling reductions up to 99% of an as-cast ingot and a subsequent 1100 or 590 °C anneal. The high temperature anneal produced a recrystallized grain structure having a wide variation in crystal orientation as determined by orientation imaging microscopy. This recrystallized specimen exhibited a net magnetostriction of ~170 ppm in the rolling direction and was well correlated with the finite element model result. The low temperature annealed specimen possessed fine elongated grains having dispersed $\{001\}\langle 110\rangle$ and $\{111\}\langle 211\rangle$ textures. Net magnetostrictions of 30 and 37 ppm were measured in the rolling direction and 45° off the rolling direction, respectively. The low magnetostriction value in the 45° direction disagrees substantially with the finite element solution of 157 ppm and suggests that unknown factors are dominating the response. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1540062]

I. INTRODUCTION

Textured polycrystalline bcc α-iron substituted with nonmagnetic gallium has the potential to serve as a versatile actuator/sensing material capable of magnetostrictive strains λ on the order of 100 ppm.[1] The anticipated large magnetostriction of such a material is suggested by the research on single crystal Fe-Ga alloys. Single crystal [100] oriented $Fe_{100-x}Ga_x$ alloys, where $13\leqslant x \leqslant 23$, exhibit magnetostrictive strains approaching 400 ppm with low saturating fields of several hundred oersteds as well as displaying a limited temperature dependence over a −20 to 80 °C range.[2,3] Furthermore, polycrystalline forms of the alloy may be mechanically robust; as-cast polycrystalline $Fe_{83}Ga_{17}$ has been shown to endure tensile stresses up to 440 MPa with elongations approaching 0.25% before failure.[4] Successfully merging the single crystal magnetostrictive performance with the polycrystalline mechanical characteristics will depend on our knowledge of the material's combined magnetic and micromechanical behavior.

To advance our understanding of how saturation magnetostriction and the elastic response of rolled polycrystalline $Fe_{83}Ga_{17}$ alloys depend on crystallographic texture and grain morphology, this work utilizes a finite element based micromechanical model (FEM) to examine the stress and strain changes within the material due to changes in magnetization. The influences of microstructural features become significant when grain dimensions are on the same order of magnitude as the overall structure or when sufficient crystallographic texturing leads to marked anisotropy in the bulk material. Our primary objective is to determine whether misalignments between the grains' crystallographic orientations result in significant internal stress thus frustrating the desired bulk magnetostrictive response. This paper reviews the anisotropic magnetostrictive reaction to changes in magnetization and the anisotropic elastic properties of cubic materials. Comparisons of FEM simulation results are made to the analytical solution for a random texture, the experimental strain measurements of a large-grained rolled specimen, and the experimental strain measurements of a fine-grained rolled specimen.

II. BACKGROUND

A magnetostrictive material's total strain response ε_{tot} to mechanical loads and saturating magnetic fields may be rep-

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resented by the linear superposition of elastic strains $\varepsilon_{\mathrm{elas}}$ and saturation magnetostriction λ_s in the relationship $\varepsilon_{\mathrm{tot}}=\varepsilon_{\mathrm{elas}}+\lambda_s$. This superposition relationship is fundamental to the three-dimensional FEM used in this work to model a polycrystal's total strain response to changes in magnetization from an ideal demagnetized state to one of full saturation in a specified direction. Although the polycrystals in these experiments are not loaded by external forces, elastic strains can arise within grains due to strains imposed by the anisotropic magnetostriction of neighboring grains possessing different crystallographic orientations. The FEM uses constant strain tetrahedrons to subdivide the material volume. Multiple tetrahedrons compose each grain and are assigned rotationally transformed elastic and magnetostrictive proprieties based on the grain orientation within a global reference frame. Continuity of displacement throughout the material is enforced at the vertices of adjacent tetrahedral elements. The FEM simulates the magnetostrictive strain, going from an ideal demagnetized state to one of saturation magnetization, by introducing a stress-free initial strain for each grain. Accounting for the elastic response of adjoining grains, the overall system is then solved for the lowest energy state to give the equilibrium condition of the system. Introductory texts provide additional details on the FEM.[5]

The magnetostrictive strains used in the FEM are obtained from a theory for the anisotropic magnetostriction of single crystals. The saturation magnetostriction is calculated using two material constants as a first order approximation. Equation (1) provides the engineering strain components for a cubic crystal magnetized to saturation from an ideal demagnetized state.[6] The direction cosines α define the saturation magnetization direction relative to the crystal axes and the magnetostriction constants λ_{100} and λ_{111} are material properties to be identified experimentally:

$$\varepsilon_{ii}\approx\frac{3}{2}\lambda_{100}(\alpha_i^2-1/3),\quad \varepsilon_{ij}=3\lambda_{111}\alpha_i\alpha_j, \tag{1}$$

where $i\neq j$, $i=1,2,3$, $j=1,2,3$. The saturation magnetostriction λ_s for an arbitrary direction is given by Eq. (2) where the β's are the direction cosines of the chosen measurement direction relative to the crystal axes:

$$\lambda_s=\sum_{i\geqslant j}\varepsilon_{ij}\beta_i\beta_j \quad \text{where } i=1,2,3, j=1,2,3. \tag{2}$$

From a practical standpoint it is difficult to achieve an ideal demagnetized state in a crystal with any certainty; however, Eqs. (1) and (2) remain quite useful. The crystal's net saturation magnetostriction $\lambda_\parallel-\lambda_\perp$ may be measured by the application of a saturating magnetic field parallel and then perpendicular to the direction of strain measurement.

After the magnetostrictive strains are introduced into the FEM, each grain's elastic response is modeled using Eq. (3). Elastic tensor strains e_j introduced by neighboring grains result in stresses σ_i proportional to the single crystal elasticity constants c_{ij}. Cubic materials such as the $Fe_{83}Ga_{17}$ alloy require only three independent elastic constants:

$$\sigma_i=c_{ij}e_j \quad \text{where } i=1,2,...,6,\ j=1,2,...,6, \tag{3}$$

$C_{11}=C_{22}=C_{33}$; $C_{12}=C_{21}=C_{13}=C_{31}=C_{32}=C_{33}$; $C_{44}=C_{55}=C_{66}$. All other $C_{ij}=0$.[7] Clark *et al.* have reported the properties for single crystal specimens of Fe-Ga alloys.[1,8] The magnetostriction constants of $\lambda_{100}=200\times10^{-6}$ and $\lambda_{111}=-16\times10^{-6}$ for $Fe_{83}Ga_{17}$ and elastic constants $c_{11}=196$ GPa, $c_{12}=156$ GPa, and $c_{44}=120$ GPa for $Fe_{81.3}Ga_{18.7}$ are used throughout this work.

III. RESULTS

To provide validation of the FEM approach, a simulation was conducted on a sheet containing 126 identically sized hexagonal shaped grains. Monte Carlo techniques were used to generate a random distribution of crystal orientations throughout multiple simulation runs. The result of interest is the total stain $\varepsilon_{\mathrm{tot},\parallel-\perp}$, which arises from a change in the saturation magnetization direction from perpendicular to one that is parallel with the direction of strain measurement. Ten runs of the FEM simulation gave $\varepsilon_{\mathrm{tot},\parallel-\perp}=80\pm3$ ppm and were accompanied by internal principal stresses ranging between ±24 MPa. For comparison, noninteracting grains having the same orientation distribution gave $\lambda_\parallel-\lambda_\perp=104\pm3$ ppm. These results are in good agreement with the analytical result $\lambda_\parallel-\lambda_\perp=(3/2)[(2\lambda_{100}+3\lambda_{111})/5]=106$ ppm. The analytical result assumes no grain interaction and may be derived from the volume integration of Eqs. (1) and (2).[9] Less regular grain shapes and sizes would likely lead to larger internal stresses and a somewhat lower bulk magnetostriction result than the 23% reduction from 104 to 80 ppm simulated here.

The next portion of the work compares the simulated and actual strain response of a rolled, high temperature annealed $Fe_{83}Ga_{17}$ specimen. The specimen was produced by a 96% hot and warm rolling reduction of an as-cast ingot. A disk specimen, 7.9 mm in diameter, was punched from the rolled material, having a final thickness of 0.38 mm. A subsequent anneal of the disk for 5 h at 1100 °C induced secondary recrystallization and produced through-thickness grains with diameters up to ~400 μm. Orientation imaging microscopy (OIM) was used to map each grain and its crystallographic orientation. Figure 1 shows only the mapped central region of the disk with the rolling direction (RD) indicated. The dashed rectangle outlines the strain gauge location used for actual and simulated strain measurements. The grains of Fig. 1 correspond to the grain misorientations, relative to a {001}⟨100⟩ sheet texture, plotted in Fig. 2. The numbered grains of Fig. 1 fall within the strain gauge region and are denoted in Fig. 2. To model the specimen with the FEM, a mesh consisting of multiple cubes was fitted to subdivide the grain structure. These cubes compose the volume of the sheet and appear as four-sided polygons at the sheet surface. Each cube is further subdivided into five tetrahedrons.

The actual and simulated strain states of the disk were analyzed for changes in the direction of the saturation magnetization vector from transverse to parallel with the rolling direction. The FEM simulation indicated $\varepsilon_{\mathrm{tot},\parallel-\perp}=177\pm3$ ppm relative to the rolling direction; this value falls between the measurements of 160 and 180 ppm collected in

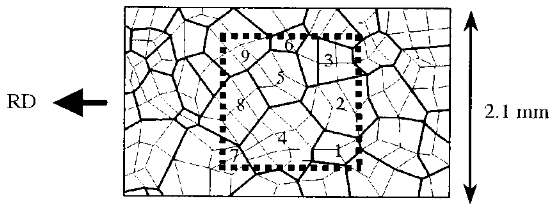

FIG. 1. Grain map and FEM mesh of 1100 °C annealed rolled $Fe_{83}Ga_{17}$. The dotted line denotes the location of the strain gauge and the numbers indicate the distinct grains.

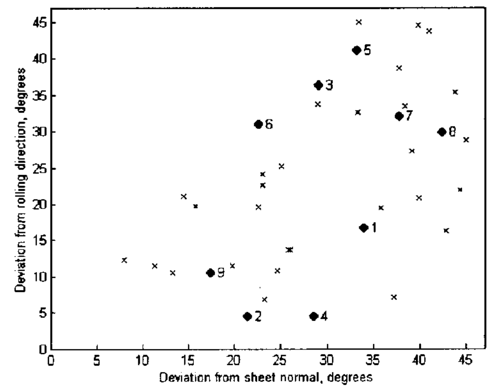

FIG. 2. Angular deviations of grains' crystallographic orientation from a {001}⟨100⟩ sheet texture in 1100 °C annealed rolled $Fe_{83}Ga_{17}$. Numbered data points (●) correspond to grains in the strain gauged area of Fig. 1. The data points indicated by × represent adjacent mapped grains.

separate strain gauge installations. Note that the experimental results are sensitive to minor changes in gauge location due to the large grain sizes and their wide range of crystallographic orientation. The FEM was also used to simulate the RD components of stress and strain for a change from a demagnetized state to one of saturation magnetization in the RD. Grains having small angular deviations from the RD (such as 2, 4, and 9) exhibit the largest magnetostrictions with $\varepsilon_{\mathrm{tot,RD}}$ ranging from 127 to 154 ppm. Variation in $\varepsilon_{\mathrm{tot,RD}}$ of these grains is influenced by compressive stress levels varying up to 3.6 MPa. These compressive stresses are the result of misoriented neighboring grains having a low $\lambda_{\parallel}$ in the RD.

A final comparison of a FEM simulation and experimental measurements was conducted on a fine-grained polycrystalline $Fe_{83}Ga_{17}$ specimen. An as-cast ingot was reduced by 99% with hot, warm, and cold rolling to a final thickness of 0.10 mm. A disk-shaped specimen of the material, 7.9 mm in diameter, was then annealed at 590 °C for 1 h to affect stress relief without secondary recrystallization. X-ray analysis indicated the presence of two predominant textures at the surface. The first texture, {001}⟨110⟩, comprises roughly 65% of the surface area with the second texture, {111}⟨211⟩, covering the balance. The angular deviation of grain orientations from both textures was assumed to follow a Gaussian distribution with one standard deviation at 20°. These textures have been previously observed to follow a Gaussian distribution in rolled iron.[10] The rolled material's grain geometry approaches a width to length to depth ratio of $50\times500\times1$ with $\sim10\ \mu$m wide grains. However, the FEM of this material used simulated grains having a width to length to depth ratio of $4\times12\times1$. Solutions to FEM simulations using increasing length ratios converged quickly, verifying that the computationally cheap grain configuration of $4\times12\times1$ should accurately represent the material's strain response. Using the two texture distributions, ten simulations were conducted on a $6\times3\times4$ matrix of grains. The strain response over interior grains was used to minimize edge effects. Relative to the rolling direction, simulations gave $\varepsilon_{\mathrm{tot},\parallel-\perp}=30\pm2$ ppm, and $\lambda_{\parallel}-\lambda_{\perp}=54\pm3$ ppm. The $\varepsilon_{\mathrm{tot},\parallel-\perp}$ result agreed with the 30 ppm experimental result. Given the large {001}⟨110⟩ texture content, simulations show that $\varepsilon_{\mathrm{tot},\parallel-\perp}\sim157\pm6$ ppm is expected at an angle of 45° from the RD, but the experimental observation of $\varepsilon_{\mathrm{tot},\parallel-\perp}=37$ ppm in this direction is inconsistent with this result. This discrepancy suggests that a significant texture change is occurring through the specimen's thickness or that the alloy's magnetostrictive characteristics have been altered during processing.

IV. SUMMARY

The FEM successfully captures the micromechanical response of polycrystalline $Fe_{83}Ga_{17}$ alloy, provided the texture is well known, and shows that principal stress magnitudes developed within the grains due to mismatches in orientation can be significant, with values up to ±24 MPa. The effect of these internal stresses can limit the total strain response by more than 20%. The cold rolled low temperature annealed experimental strain response does not agree with simulations, suggesting that a significant physical characteristic of the material has not been accounted for.

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